

THE SPIN OF THE BLACK HOLE GS 1124-683: OBSERVATION OF A RETROGRADE ACCRETION DISK?

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ABSTRACT

We re-examine archival *Ginga* data for the black hole binary system GS 1124-683, obtained when the system was undergoing its 1991 outburst. Our analysis estimates the dimensionless spin parameter $a_* = cJ/GM^2$ by fitting the X-ray continuum spectra obtained while the system was in the “Thermal Dominant” state. For likely values of mass and distance, we find the spin to be $a_* = -0.25^{+0.05}_{-0.64}$ (90% confidence), implying that the disk is retrograde (i.e. rotating antiparallel to the spin axis of the black hole). We note that this measurement would be better constrained if the distance to the binary and the mass of the black hole were more accurately determined. This result is unaffected by the model used to fit the hard component of the spectrum. In order to be able to recover a prograde spin, the mass of the black hole would need to be at least $15.25 M_\odot$, or the distance would need to be less than 4.5 kpc, both of which disagree with previous determinations of the black hole mass and distance. If we allow f_{col} to be free, we obtain no useful spin constraint. We discuss our results in the context of recent spin measurements and implications for jet production.

Subject headings: accretion, accretion disks, black hole physics, spin

1. INTRODUCTION

Spinning black holes (BHs) are of fundamental importance to astrophysics, because they represent laboratories for the exploration of General Relativity. Spin is constrained by indirect measures involving the accretion disk. A low-mass X-ray binary (LMXB) is an example of a binary in which the black hole (or neutron star) is orbited by a small star, usually with a mass less than that of the Sun. The star usually fills its Roche lobe and its outermost layers of gas are stripped off its surface by the immense gravity of the compact object, and form an accretion disk.

In periods of increased accretion activity, X-ray Novae can occur. X-ray Novae are generally transient phenomena, waiting on average 10-50 years between outbursts (Tanaka & Shibazaki 1996). Attempts to create a unified model of the disk evolution in these outbursts (Esin et al. 1997) have led to the description of the outbursts as the combination of a thin accretion disk and an Advection Dominated Accretion Flow (ADAF). Observationally, these two migrate through several spectral states (see e.g. Reynolds & Miller 2013). The state important to this analysis is the Thermal Dominant State (TD state, formerly referred to as High State or High/Soft state), in which the disk extends all the way to the innermost stable circular orbit (ISCO), and dominates the emission (Esin et al. 1997). Since the ISCO is entirely dependant on the spin ($r_{\text{ISCO}} = 6r_g$ for a schwarzschild BH, $r_{\text{ISCO}} = r_g$ for a maximally prograde BH, $r_{\text{ISCO}} = 9r_g$ for a maximally retrograde BH), measurements of the radius of the ISCO can be used to determine the spin of the BH. This is the idea behind the continuum fitting method, in which one fits a model of a thin accretion disk to Thermal Dominant State spectra of a BH to estimate the ISCO, and thus infer the spin (Zhang, Cui, & Chen 1997, Schafee et al. 2006, McClintock et al. 2006, etc.). Spin can also be measured by modeling the broadened Iron K-shell emission line that originates in the inner disk (e.g. Tanaka et

al 1995, Miller et al. 2002, Miller et al. 2004).

A common XSPEC model to describe the thin accretion disk is *kerrbb* (Arnaud 1996; Li et al. 2005). This model stands out since it takes the spin as a parameter used to define the model spectrum. It also includes relativistic effects such as limb-darkening or self irradiation of the disk. In order for this method to be used to estimate spin, the mass, distance, and inclination angle of the disk must be known (Zhang, Cui, & Chen 1997). Additionally, the spin measurement is dependent on the color correction factor ($f_{\text{col}} = T_{\text{col}}/T_{\text{eff}}$). Again, *kerrbb* is useful, since it accepts all of these as input model parameters. Other new models, such as *simpl* (Steiner et al. 2009a) offer an improved description of the hard component relative to a powerlaw. The pairing of *kerrbb* and *simpl* have been used several times to measure spin (see for example Gou et al. 2009, Steiner et al. 2010, etc).

2. SOURCE AND DATA SELECTION

GS 1124-683 (also called Nova Muscae 1991) is a LMXB that underwent an outburst in 1991. It was discovered in January 1991 by the All Sky monitors on both the *Ginga* satellite, and the *Granat* satellite (Makino et al. 1991; Lund & Brandt 1991; Kitamoto et al. 1992; Brandt et al. 1992). It flared up to a maximum flux of 8 Crab (1.92×10^{-7} ergs cm⁻² s⁻¹) on January 15, and subsequently decayed exponentially with a timescale $\tau = 30$ days (Ebisawa et al. 1994). It was studied using *Ginga* (Ebisawa et al. 1994) over the course of several months, during which it migrated through all 5 of the typical spectral states.

The BH mass, distance, and inclination have been refined several times. Shahbaz et al. (1997) modeled the infrared light curve to deduce the BH mass, the mass of the secondary star, the binary separation, and the binary inclination. They also inferred from these the distance to the BH using Bailey’s relation (Bailey 1981). In fact the distance to GS 1124-683 has been revised by several authors (Della Valle et al. 1991; Orosz et al. 1996; Shahbaz et al. 1997; Gelino et al. 2001), the most recent of which being Gelino (2004, Hereafter G04), who refined the method from Gelino et al. (2001; the refined method is described in Gelino, Harrison, & Orosz 2001) and

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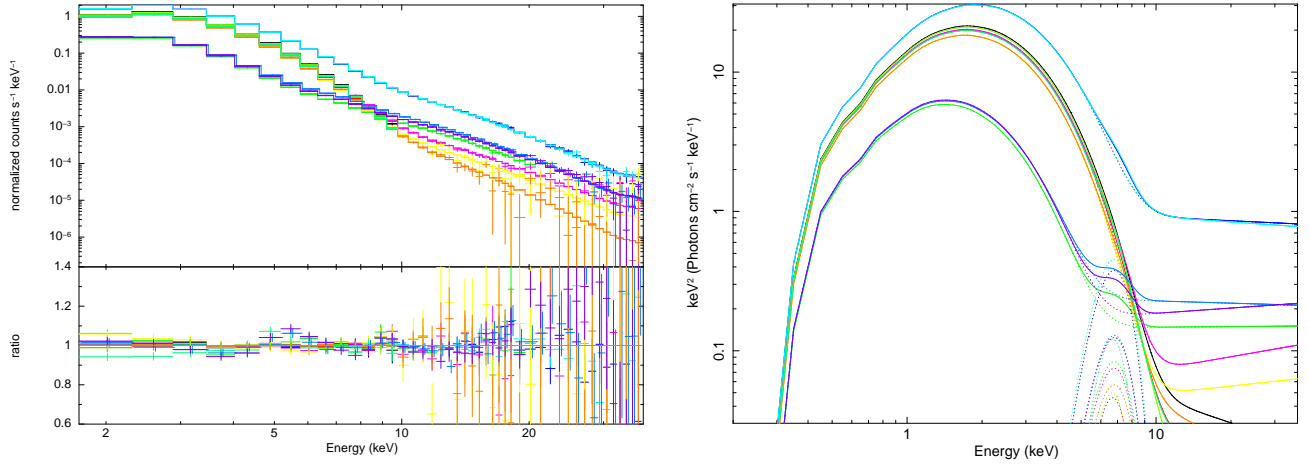


FIG. 1.— (Left) All spectra of GS 1124-683 used in our analysis, and the data to model ratios. The large errors above 20 keV are as a result of diminishing sensitivity at higher energy. (Right) Best fit model to our data. In all cases the disk dominates the emission, and in several of the spectra, the hard component becomes very faint

found the distance to be 5.89 ± 0.26 kpc, which falls within the range allowed by Orosz et al. (1996), but is better constrained. The inclination angle measurement is much better agreed upon, with the value from G04 of $54^\circ \pm 1^\circ.5$ agreeing with that from Shahbaz et al. (1997). The mass is also fairly well agreed upon, with the measurement of $7.24 \pm 0.70 M_\odot$ from G04 corresponding to those made previously by Shahbaz et al. (1997), and those made by Orosz et al. (1996). We used the best fit values from G04 for mass, distance, and inclination because they are newer and better-constrained than other determinations, and since they were found using infrared photometry, from which the disk and hotspot produce less contamination in the light curve. It should also be noted that we assume the inclination angle of the inner disk to be the same as that of the binary, which is not necessarily the case (e.g. Maccarone 2002).

The X-ray data we consider are those presented in Ebisawa et al. (1994). For the continuum fitting method, we want to use spectra obtained when the source was in the TD state. As per McClintock et al (2006), we selected disk luminosities less than 30% of the Eddington limit, and restricted our observations to those in which the soft flux contributes at least 90% of the total flux ($F_{\text{soft}}/F_{\text{tot}} \geq 0.9$) based on the results reported in Ebisawa et al. (1994). Assuming a distance of 5.89 kpc (G04), we find that the peak luminosity reached was 7.97×10^{38} ergs s^{-1} , which, assuming a black hole mass of $7.24 M_\odot$ (G04), is about $0.87 L_{\text{edd}}$. Assuming an exponential decay with a timescale of 30 days (Ebisawa et al. 1994), we find that observations falling into our luminosity criterion begin 32 days after January 15 (February 16). Observations falling into our hardness criteria began on February 16 as well, and ended on May 18, when the source transitioned to the Low/Hard state.

Some spectra required additional consideration due to anomalous behaviors they exhibited. As noted in Ebisawa et al. (1994), observations occurring in late March and throughout April had a hard component that was too faint to be observed by the *Ginga* detectors. For those spectra (March 28, 29, 30, and April 2), we were required to ignore outside of the energy range 1.2-10 keV. For the first of the May 17 spectra, the hard component became too faint to be observed at energies exceeding 25 keV, so we ignored those energies in that

spectrum. We also ignored the April 19 observation altogether because it required an excessively low color correction factor in order for the spin to be consistent with the other observations (1.36), and because it had a χ^2_ν value that was too high (~ 3) when f_{col} was required to be within our allowed range (1.5-1.9, see Shimura & Takahara 1995). For all other observations, we examined over the entire reliable energy range for data obtained with *Ginga*; 1.2-37.0 keV (Ebisawa 1991).

3. ANALYSIS

All analysis was performed in XSPEC version 12.8.0 (Arnaud 1996). The model central to our analysis is *kerrbb* (Li et al. 2005), which models a thin accretion disk around a Kerr black hole. *Kerrbb* is convolved with *simpl* (Steiner et al. 2009a), an empirical model for Comptonization. This model provides a more physical description of the hard component (as opposed to *powerlaw*), and yields fits of equal statistical quality. It also has the virtue of simplicity compared to more rigorous models of Comptonization (such as *compTT* or *compBB*).

In addition, we included the effects of absorption by the interstellar medium, *tbabs* (Wilms, Allen, & McCray 2000). We fixed the hydrogen column density to $1.5 \times 10^{21} \text{cm}^{-2}$, which is the best-fit value found for N_H in Ebisawa et al. (1994). We also found it necessary to add a Gaussian line with energy 6.5 keV, and with its width allowed to vary between 0 and 1 keV. Relativistic lines did not improve the fit by a statistically significant margin. Altogether, this model is shown in Figure 1.

We fixed the mass, distance, and inclination to the measurements given by G04, and fixed the norm of *kerrbb* to 1, as should be done when mass, distance, and inclination are fixed (Shafee et al. 2006, McClintock et al. 2006, etc.). We did not include the effects of limb-darkening. We allowed the spin (a_*), effective mass accretion rate (\dot{M}), photon index (Γ), and fraction of the seed photons scattered (f_{sc}) to vary freely and unconstrained, and the color correction factor f_{col} to vary between 1.5 and 1.9 (Shimura and Takahara 1995). We added a 2 percent systematic error to all energy bins to ensure acceptable fits, typical for analyses of *Ginga* data.

We fitted spectra individually at first. For those fits that ignored large portions of the hard component, the spins were not very well constrained. In order to place tighter constraints on the spin, we found it better to jointly fit all spectra. For

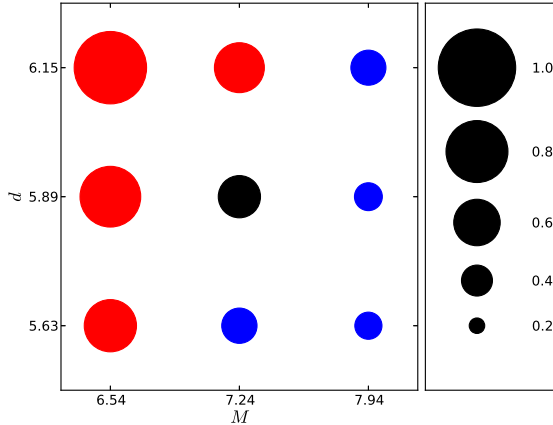


FIG. 2.— Results of a Grid search through the mass/distance parameter space. The size of the circles is proportional to the magnitude of the spin $|a_*|$. Circles filled blue have lower χ^2 than the fit using the best-fit mass and distance in G04 ($439.0 \leq \chi^2 \leq 441.5$), and the red circles have higher χ^2 ($443.0 \leq \chi^2 \leq 447.0$). All above fits have $\nu = 344$.

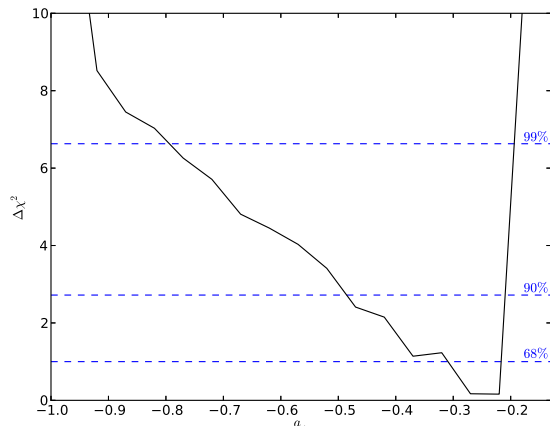


FIG. 3.— Spin Contours for GS 1124-683 obtained while holding mass and distance within the parameter space used for the grid search, but allowing them to be variable, jointly-determined parameters. Horizontal dotted lines are drawn at the 68%, 90%, and 99% confidence levels.

joint fits, we required the spin, and spectral hardening factor to be jointly determined, and allowed the rest to vary as before.

To examine the full allowable parameter space (since we do not have entirely precise measurements of mass and distance), we did a 3×3 grid search of mass and distance, fitting the spectra for each pairing, finding the best fit parameters, and estimating their uncertainties. The points on our grid correspond to the best fits of mass and distance from G04, and their upper and lower limits. The uncertainty found here propagates into the uncertainty in our spin measurement, since it is entirely allowed that the BH could have any coupling of parameters within that grid. To globally cover this space, and to find the best-fit values of all parameters, we fitted with mass and distance required to be jointly determined, but allowed to vary within this grid range.

4. RESULTS

Table 1 shows the results of spectral fitting. The best-fit value of the spin is $a_* = -0.25^{+0.05}_{-0.64}$, implying that the spin is

retrograde. The lower bound here is very relaxed, since our analysis allows uncertainty to propagate from uncertainties in the mass and distance without taking account of the statistical preferences inside of our allowed range. Figure 2 shows the result of the grid search, which expresses the extent at which different pairings of mass and distance affect our measurement of the spin. For all parameters, the uncertainties expressed in Table 1 reflect the upper and lower limits estimated from our grid search. The χ^2_ν values for this analysis favor a smaller magnitude of the spin, smaller magnitudes of the distance, and larger masses for the BH than the best-fit values from G04.

To place a tighter constraint on a_* while taking account of our uncertainties in the mass and distance, we allowed M and d to vary within our grid range but kept them jointly determined. We did fits stepping through 20 evenly spaced values of a_* between -0.97 and 0.03 using *steppar*. Figure 3 shows the result. Here the best fit value for the spin lies between -0.5 and -0.2 with 90% confidence, which is better-constrained than the value estimated from the grid search since it takes account of the behavior of χ^2 with respect to mass and distance rather than the grid search, which treats each pairing as equally likely. The spin here is greater than -1.0 at just over 3σ , is less than -0.15 at the 6σ level, and is less than 0 at $>> 8\sigma$ (the p-value for $a_* = 0$ is $\sim 10^{-102}$). We choose to use the confidence range estimated from our grid search however, since it was calculated with M and d fixed, which is a necessity for finding spin by fitting the continuum.

As a check on our results, we decided to examine the behavior of a_* as we changed certain other parameters, namely the color correction factor f_{col} . This is a useful check, since our value of f_{col} is close to the minimum of the allowed range. We fixed its value to 1.7 and fit all other parameters. We find that raising the value of f_{col} even this high results in the spin immediately being pegged at $a_* = -1$, the theoretical limit. This further solidifies our determination of a_* as being retrograde.

5. DISCUSSION

A retrograde spin is atypical in a black hole LMXB. Nonetheless our measurement is consistent with previous attempts to measure the spin for GS 1124-683. Suleimanov et al (2008) constrained it to be ≤ 0.4 , and Zhang, Cui, and Chen (1997) estimated it to be nearly Schwarzschild, yet retrograde (-0.04). Although our method is descendant from Zhang et al. (1997), ours yields a different measurement of the spin since it takes advantage of newer models developed (*kerrbb* & *simpl*), which provide a more physical description of the spectrum, and allow for relativistic effects. Recent works (Reis et al. 2013, Gou et al. 2010) have measured spins for SWIFT J1910.2-0546 and A06200-00 that are either retrograde, or consistent with being retrograde, implying that such spins are less rare than previously thought.

Furthermore, as shown in Figure 3, our upper limit to the spin is still retrograde. If the spin is actually prograde one of two things must be true. Either the distance must be considerably smaller than that given by G04, or the BH mass must be larger. To find out how much closer, or more massive it needs to be, we fixed either mass or distance to their best determination from G04, and slowly raised or lowered the other until their best fit value of a_* was greater than 0. When we varied the mass, and held the distance constant, we found that GS 1124-683 must have $M_{\text{BH}} \geq 15.25 M_\odot$. This is in disagreement not only with G04, but also with Shahbaz et al. (1997), who constrained the BH mass to be less than $10.5 M_\odot$ at the

TABLE 1
SPECTRAL FITTING RESULTS

| Time (UT; 1991) | Γ | f_{sc} (10^{-3}) | a_* (cJ/GM^2) | M (10^{18} g s^{-1}) | f_{col} | σ (keV) | norm ($10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}$) |
|--------------------|------------------------|----------------------------------|-------------------------|---------------------------------------|------------------------|------------------------|--|
| 2/20 23:31-23:36 | $2.08^{+0.04}_{-0.03}$ | $13.9^{+1.0}_{-0.7}$ | $-0.25^{+0.05}_{-0.64}$ | $8.0^{+4.1}_{-0.2}$ | $1.51^{+0.10}_{-0.01}$ | $1.0^{+0}_{-0.07}$ | 22 ± 3 |
| 2/21 0:23-0:29 | $2.12^{+0.04}_{-0.03}$ | $14.8^{+1.1}_{-0.8}$ | $-0.25^{+0.05}_{-0.64}$ | $8.0^{+4.1}_{-0.2}$ | $1.51^{+0.10}_{-0.01}$ | $1.00^{+0}_{-0.04}$ | 26^{+4}_{-3} |
| 3/8 18:04-18:21 | $1.68^{+0.11}_{-0.09}$ | $0.9^{+0.2}_{-0.1}$ | $-0.25^{+0.05}_{-0.64}$ | $5.5^{+2.8}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | $1.0^{+0.0}_{-0.03}$ | $4.1^{+1.0}_{-0.7}$ |
| 3/10 16:56-17:16 | 1.8 ± 0.3 | $0.8^{+0.5}_{-0.3}$ | $-0.25^{+0.05}_{-0.64}$ | $5.0^{+2.6}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | $1.0^{+0}_{-1.0}$ | $0.7^{+1.1}_{-0.7}$ |
| 3/20 12:56-13:56 | $2.8^{+0.3}_{-0.2}$ | $2.5^{+1.4}_{-0.7}$ | $-0.25^{+0.05}_{-0.64}$ | $5.0^{+2.6}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | $1.0^{+0.0}_{-0.1}$ | $3.1^{+1.0}_{-0.7}$ |
| 3/28 9:37-9:42 | 2.6 (<i>frozen</i>) | $2.0^{+0.4}_{-0.3}$ | $-0.25^{+0.05}_{-0.64}$ | $5.8^{+3.0}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | $0.4^{+0.6}_{-0.4}$ | $0.7^{+1.5}_{-0.7}$ |
| 3/29 5:54-6:05 | 2.6 (<i>frozen</i>) | 0.6 ± 0.3 | $-0.25^{+0.05}_{-0.64}$ | $5.7^{+2.9}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | $0.8^{+0.2}_{-0.3}$ | $2^{+1.2}_{-0.8}$ |
| 3/30 8:36-8:53 | 2.6 (<i>frozen</i>) | $1.1^{+0.4}_{-0.2}$ | $-0.25^{+0.05}_{-0.64}$ | $5.4^{+2.8}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | 0.8 ± 0.1 | $5.4^{+1.1}_{-0.7}$ |
| 4/2 5:04-5:29 | 2.6 (<i>frozen</i>) | $1.1^{+0.9}_{-0.2}$ | $-0.25^{+0.05}_{-0.64}$ | $5.4^{+2.8}_{-0.1}$ | $1.51^{+0.10}_{-0.01}$ | 0.8 ± 0.2 | $2.0^{+1.1}_{-0.7}$ |
| 5/17 3:12-3:19 | $1.98^{+0.08}_{-0.07}$ | 9^{+2}_{-1} | $-0.25^{+0.05}_{-0.64}$ | $1.73^{+0.9}_{-0.03}$ | $1.51^{+0.10}_{-0.01}$ | $1.00^{+0.0}_{-0.07}$ | $4.8^{+0.5}_{-0.6}$ |
| 5/17 4:34-4:56 | $1.88^{+0.05}_{-0.04}$ | $9.0^{+1.1}_{-0.7}$ | $-0.25^{+0.05}_{-0.64}$ | $1.85^{+0.95}_{-0.03}$ | $1.51^{+0.10}_{-0.01}$ | $1.00^{+0.00}_{-0.05}$ | $7.0^{+0.4}_{-0.5}$ |
| 5/17 7:49-8:09 | 2.05 ± 0.04 | 15 ± 1 | $-0.25^{+0.05}_{-0.64}$ | $1.81^{+0.93}_{-0.03}$ | $1.51^{+0.10}_{-0.01}$ | $1.00^{+0.00}_{-0.02}$ | 7.4 ± 0.5 |

NOTE. — Results of joint spectral fits to the observations in our sample. The χ^2 value for the best fit is 439.57 (342 DOF).

90% confidence level using the maximum mass of the secondary star (Inferred from the spectral type). This makes a mass of $15.25 M_\odot$ unlikely, so if the black hole is prograde, it is more likely that the distance to the binary is lower. In fact, in order for the spin to be prograde, the distance would have to be $d \leq 4.5$ kpc, still greater than the maximum allowed distance from Shahbaz et al. (1997). If we take their entire range of mass and distance into account however, and perform a grid search, we find that the spin found using their best determination of the mass and distance is still retrograde ($a_* = -0.16$ for $M = 5.8 M_\odot$ and $d = 4$ kpc), there is no lower bound on a_* , and the upper bound is $a_* < 0.7$.

Other models, such as that from Ebisawa et al. (1994), which assume $a_* = 0$ are also incompatible with the mass and distance of G04. These models suggest that the mass would need to be at least $16 M_\odot$ or the distance would need to be less than 2.65 kpc in order to measure an inner radius consistent with $a_* = 0$. An additional way to retrieve a retrograde spin would be to lower f_{col} to 1.0, which is suggested by our measured value existing near the hard limit of 1.5. If we allow f_{col} to be free, we find that its best fit is $f_{\text{col}} = 1.17^{+0.35}_{-0.28}$, but the spin no longer has any constraint. We choose to use our range of f_{col} because these are the range of values expected for the range of luminosities in our sample (Shimura & Takahara 1995). The Ebisawa et al. (1994) model can also be fixed by increasing r_{in} , implying $a_* < 0$.

To examine how a_* is affected by the hard component of the spectrum, we tried using *powerlaw* instead of *simpl* to model the hard component. This represents a less physical model than *simpl*, but it produces a check on our result. For these fits Γ and the normalization were allowed to be free and independent between spectra. When this model is fitted to the data, we find the spin to be $a_* = -0.46^{+0.02}_{-0.23}$, consistent with the result obtained using *simpl*.

It is also interesting to consider how our result fits into the context of jet production, since very few retrograde spins have been observed, making GS 1124-683 an interesting test of current empirical models. One such model was suggested by Narayan & McClintock (2012), which suggests that the scaled jet power is proportional to the black hole spin. This model

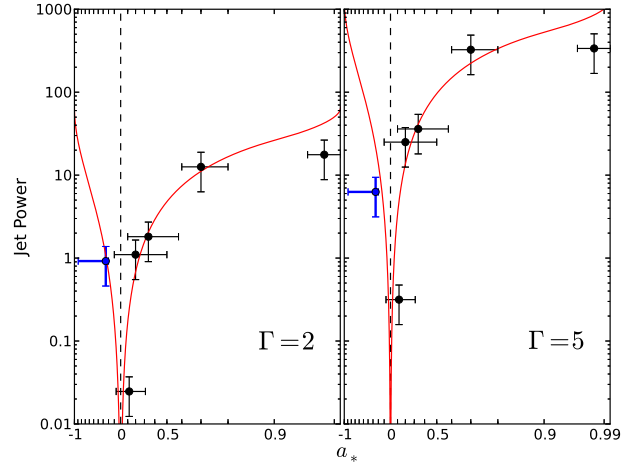


FIG. 4.— Comparison of our measured spin and the calculated jet power (blue) with the best fit empirical model from Narayan & McClintock (2012), and with H1743-322 (added in Steiner, McClintock & Narayan 2013), having $\Gamma = 2$ (left) or $\Gamma = 5$ (right).

was used by Steiner, McClintock & Narayan (2013) to predict the spins of 6 black holes including GS 1124-683. In their analysis, they only considered prograde spins, as no retrograde spins had been observed using the CF method at that time. To calculate jet power, we used their prescription:

$$P_{\text{jet}} = \left(\frac{\nu}{5 \text{ GHz}} \right) \left(\frac{S_{\nu,0}^{\text{tot}}}{\text{Jy}} \right) \left(\frac{D}{\text{kpc}} \right)^2 \left(\frac{M}{M_\odot} \right)^{-1} \quad (1)$$

where $S_{\nu,0}^{\text{tot}}$ is the beaming corrected flux.

$$S_{\nu,0}^{\text{tot}} = S_{\nu,\text{obs}} \times (\Gamma[1 - \beta \cos i])^{3-\alpha} \quad (2)$$

Γ is the lorentz factor, which we assumed to be 2 (to compare to their derived relationship for $\Gamma = 2$. It should be noted that Γ is likely not the same for all jet sources.), α is the radio spectral index, which is 0.5-0.6 for GS 1124-683 (Ball et al. 1995). β follows from Γ , and i is the inclination of the system,

for which we used 54° (G04), since we used the same value to measure the spin. Using the maximum radio flux suggested by Ball et al. (1995) of ≈ 0.2 Jy, the scaled jet power is then ≈ 0.92 in natural units. Arbitrarily assuming an error in the radio flux of a factor of ≈ 0.5 (following the methodology of Narayan & McClintock 2012), and using our determination of spin found from our steppar run, we find that our spin measurement is consistent with their best fit model (see Figure 4) which predicts $P_{\text{jet}} = 1.08^{+0.69}_{-0.43}$ for $a_* = -0.25$. It is different from the determination of the spin in Steiner, McClintock, & Narayan (2013) only because they had assumed that the spin would be prograde, and because they used values for mass and inclination different from the measured mass and inclination. We note that a full consideration of the current data does not find strong evidence that spin powers jets, with \dot{M} or $|\mathbf{B}|$ potentially acting as a throttle (King et al. 2013).

6. CONCLUSIONS

- (1) For the most recent determinations of mass and distance to GS 1124-683, the spin is most likely $-0.25^{+0.05}_{-0.64}$. There is an upper limit to the spin of -0.15 (6σ level). This result is independent of the model used to fit the hard component.
- (2) Keeping the distance held within the constraints from G04, the minimum mass for GS 1124-683 where we can derive a prograde spin is $M = 15.25 M_\odot$.
- (3) Keeping the mass held within the constraints from G04, the maximum distance from which we can potentially resolve a prograde spin is $d = 4.5$ kpc.
- (4) If we require the color correction factor f_{col} to be fixed at 1.7 for all spectra, the spin becomes pegged at the hard limit of -1 . The upper limit necessary to avoid this is $f_{\text{col}} = 1.67$.
- (5) GS 1124-683 agrees with the empirically derived relationship between black hole spin and jet power from Narayan & McClintock (2012) with $\Gamma = 2$, though there are many caveats and assumptions.

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